THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of

G. S. Kino

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ABSTRACT

I. MICROWAVE AMPLIFICATION IN GaAs

Evidence of accumulation layer oscillations in GaAs diodes with $n\ell$ product value of about 5×10^{11} cm^{-2} is presented.

A noise measurement was performed on a pulsed GaAs amplifier with a resulting noise figure of 36 dB.

A thin film GaAs amplifier, utilizing carrier wave propagation along the film, has been fabricated and is described. Initial amplifier gain test results are given.

II. GUNN OSCILLATOR STUDIES

The growth of GaAs epi-layer in a vertical system has been evaluated in an effort to grow thin layer homogeneous layers of good quality. In the range of thickness from 20-40 μ we have obtained carrier concentrations of $7 \times 10^{14}/\text{cm}^3$ when a quartz crucible was used in place of the graphite. The mobility is not yet as high as that obtained in the horizontal system. The devices as now fabricated are capable of withstanding continuous fields at the threshold of oscillation but it is still necessary to operate pulse as one increases the field above the threshold values. The computer program has been concentrated on space charge decay along the length of the device for a given frequency as both the length and the carrier concentrations have been varied.

INTRODUCTION

The work under this Grant is generally concerned with communication and information processing in space satellites and more particularly concerned with exploring new devices, particularly solid-state and optical devices, suitable for generation and modulation of electromagnetic waves in the microwave range and upward through the millimeter and optical frequency ranges. Two projects were active under this Grant during the reporting period:

I. Microwave Amplification in GaAs

II. Gunn Oscillator Studies

The Responsible Investigator for this Grant is G. S. Kino.

I. MICROWAVE AMPLIFICATION IN GaAs

(G. S. Kino, B. Fay, and H. Weil)

INTRODUCTION

The objective of this work is to realize a two port unilateral space charge wave amplifier based on the Gunn effect and to check the theory of wave propagation in finite semiconductors.

The active medium consists of a GaAs diode biased between the negative differential conductance threshold and the threshold for current oscillations, the latter being a function of the diode $n\ell$ product as well as of its thickness and dielectric environment.

PRESENT STATUS

1. HIGH RESISTIVITY BULK GaAs AMPLIFIER

A. Accumulation Layer Oscillations

In our two-port amplifier experiments we have found that GaAs diodes with more than 30 dB of internal small signal gain, i.e., with an $n\ell$ product greater than or equal to 2×10^{11} cm^{-2}, break into oscillations at large bias voltages (the amplifier being operated always below this oscillation threshold).

A numerical solution of the one dimensional Gunn effect equations, including the effect of nonuniform dc fields, shows that for a short circuited diode (i.e., one with a small load impedence), current oscillations associated with a drifting electron accumulation layer are to be expected when the $n\ell$ product exceeds 2×10^{11} cm^{-2}.

The computed current vs time waveform assumes a triangular wave shape which is very similar to the observed current waveform in such samples, as illustrated in Fig. 1. The accumulation layer mode of oscillation has been shown[1,2] to be the fundamental mode of oscillation in diodes with perfectly uniform doping. However, the small doping fluctuations inherent in a real diode inevitably cause a transition to a dipole layer mode of oscillation which is commonly observed experimentally with diodes having $n\ell$ product values in excess of 10^{12} cm^{-2}.

By performing capacitative probe measurements on lightly doped (300 ohm-cm) long diodes (1 mm) with $n\ell$ product values of about 5×10^{11}cm^{-2}, we have found evidence of the accumulation layer mode of oscillation in those samples. The relatively high resistivity results in a small convective growth rate which minimizes the effect of doping fluctuations. Figure 2 shows the potential distribution across the length of the diode at four different instants of time, T_1 to T_4 , spaced 2 nsec apart; the oscillation period in this case being 6.8 nsec. At times T_1 and T_2 the low field and high field regions characteristic of traveling accumulation layer are clearly displayed. At time T_3 , the accumulation layer has nearly reached the anode and a weak depletion layer has formed behind it. At time T_4 , the accumulation layer has been absorbed at the anode and a new one is forming some distance away from the cathode.

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[1]D. E. McCumber and A. G. Chynoweth, "Theory of Negative-Conductance Amplification and of Gunn Instabilities in 'Two-Valley' Semiconductors," IEEE, PGED, ED-13, No. 1, p. 4 (January 1966).

[2]H. Kroemer, "Nonlinear Space Charge Domain Dynamics in a Semiconductor with Negative Differential Mobility,", IEEE PGED, ED-13, No. 1, p. 27. (January 1966).

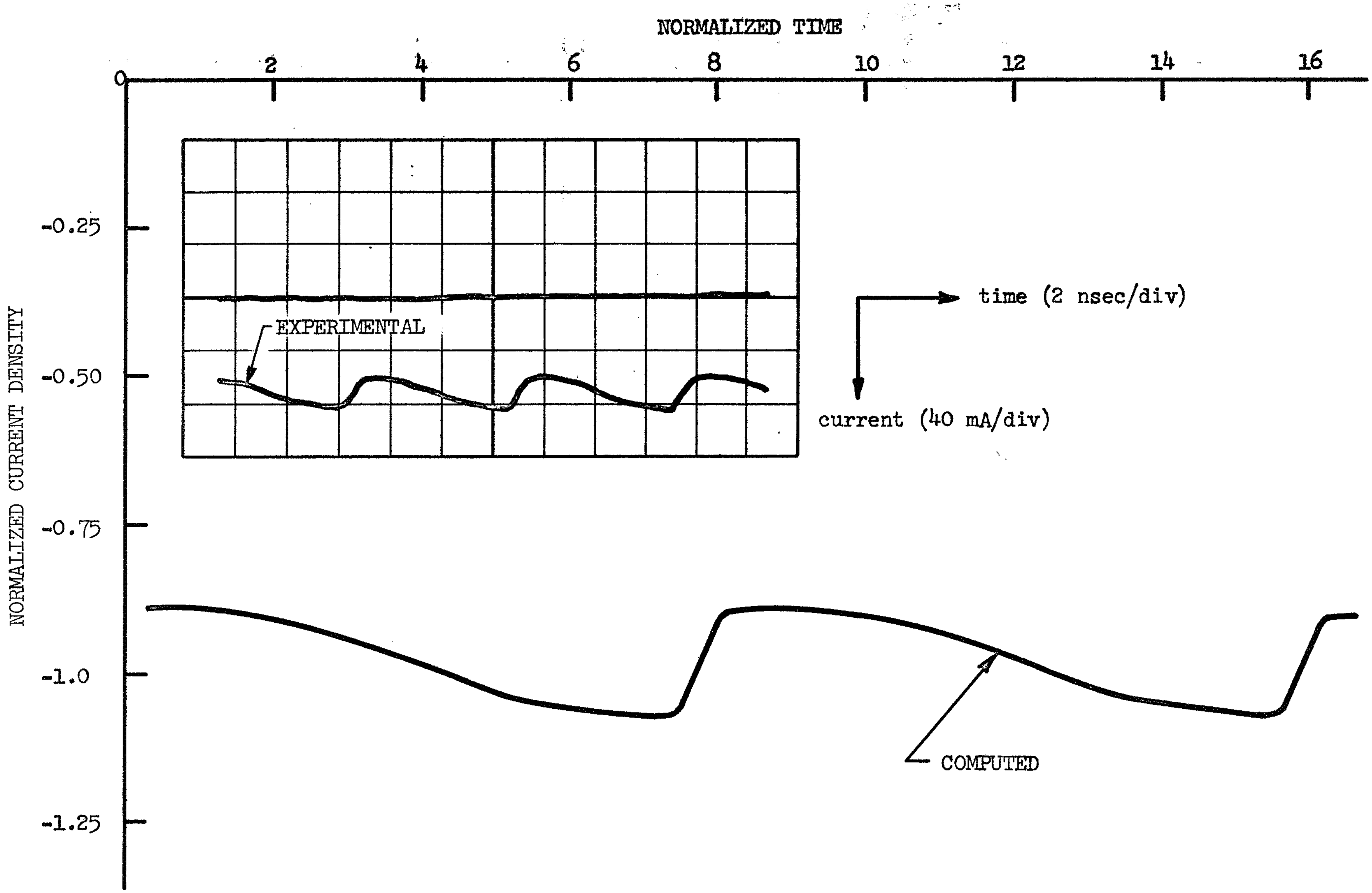

FIG. 1--Current waveforms (Computed and experimental)
$NL = 2 \times 10^{11}$ cm^{-2} $L = 10^{-1}$ cm.

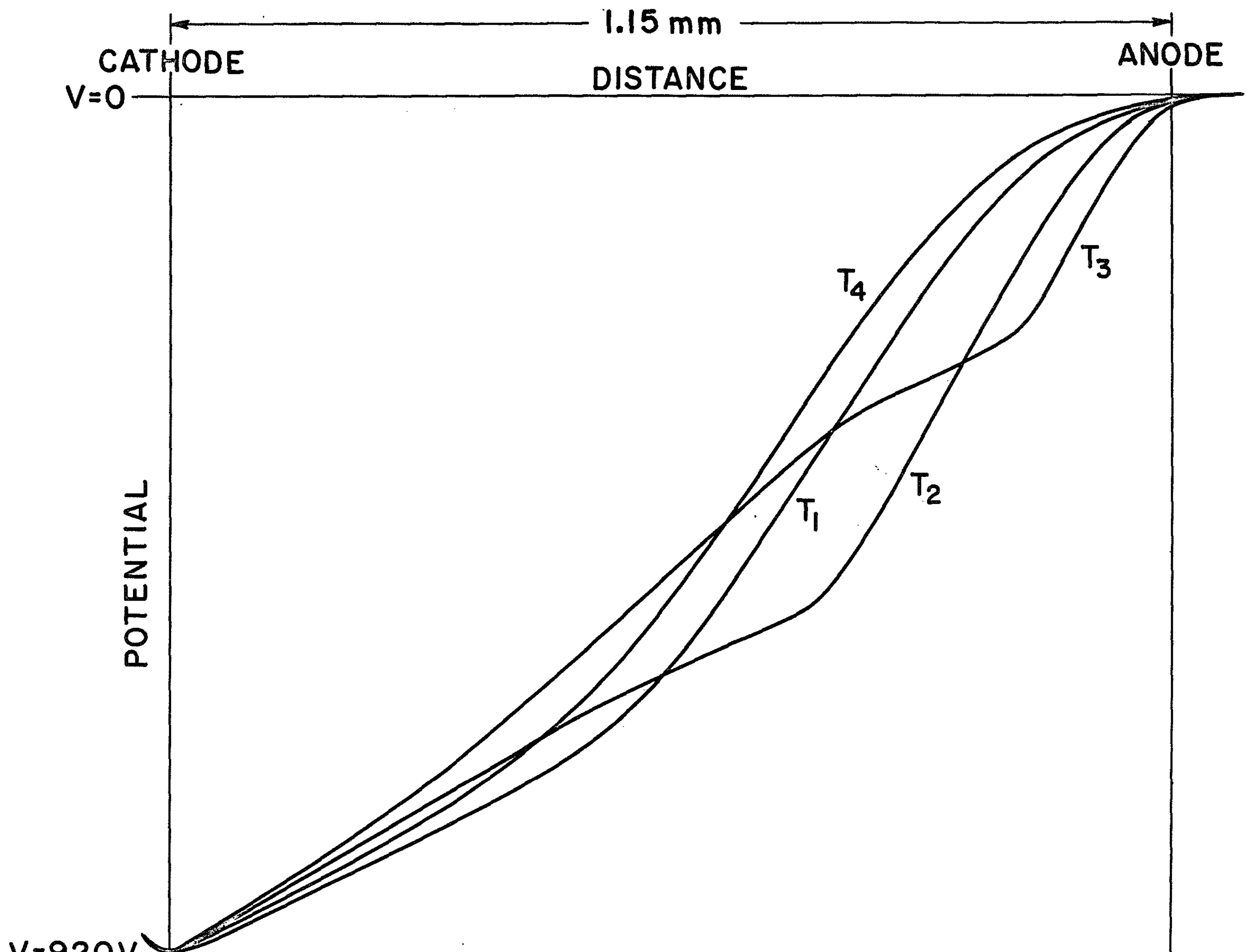

FIG. 2--Potential distribution along diode at different times.
$NL = 5 \times 10^{11}\ cm^{-2}$

B. Noise Figure of GaAs Amplifier

We have performed some noise measurements on our pulsed GaAs amplifier using a wide bandwidth measuring system as described by Levine.[3]

Our initial measurements were made on thick (0.6 mm) specimens, and we have observed a noise figure of 36 dB for one sample with 22 dB of net terminal gain and 5.5 MHz tuned bandwidth at 990 MHz.

This high noise figure is to be expected because of the high input impedance and relatively high dc current of the device. A simple calculation of the noise figure starting from the cathode shot noise formula

$$\langle I^2 \rangle = 2eI_0 \Delta f$$

leads to a noise figure formula

$$F = 1 + \frac{2eI_0 Z_0}{kT}$$

In the experiment, the input impedance Z_0 is approximately $1\ k\Omega$, the drift current I_0 is 80 mA, yielding a noise figure of 38 dB which is in excellent agreement with the measurement. A diode designed for low noise should be used with low matching impedances of the order of 50 ohms and with much lower drift current. This requires a diode of small cross section. In such a case it should be possible to obtain noise figures below 10 dB.

We have recently obtained some bulk GaAs in the 50-100 ohm-cm range and are undertaking a new series of measurements with thinner and shorter samples.

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[3] P. A. Levine, "Measurement of AM Noise in Pulsed Oscillators and Amplifiers," to appear in Proc. IEEE (Correspondence).

2. LOW RESISTIVITY EPITAXIAL GaAs AMPLIFIER

A. Introduction

Preliminary theoretical studies were conducted on a thin epitaxial film version of the high resistivity bulk material GaAs traveling wave amplifier. The studies showed that such an amplifier could (1) be capable of power gain at high microwave frequencies, (2) have very practical impedance levels (50 ohm type) over very broad frequency bandwidths, (3) have reasonably low amplifier noise figures (i.e., of the order of 10 dB), and (4) be capable of cw operation and reasonable efficiencies due to its physical structure.

B. Theoretical Study

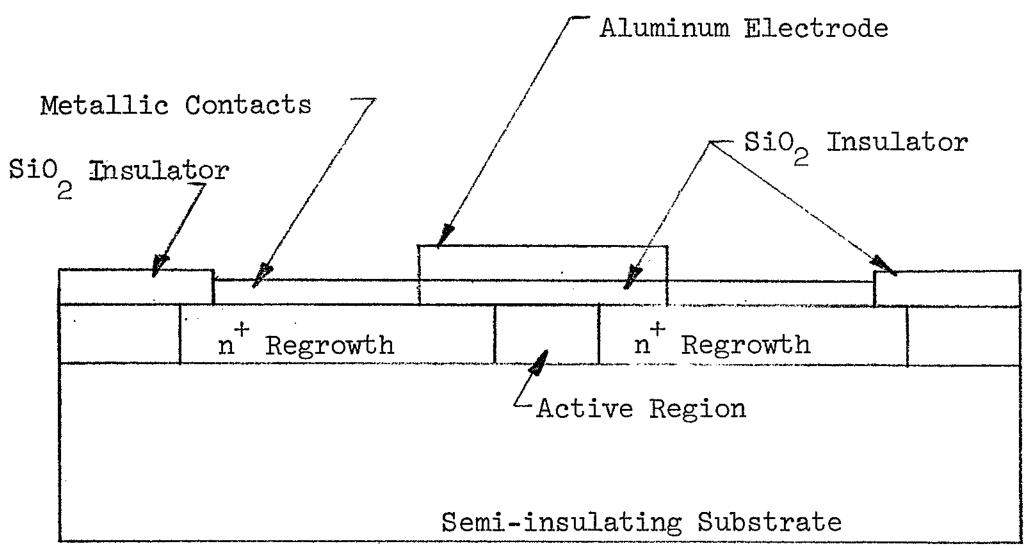
Computer programs were written to solve the very complex dispersion equations describing the behavior of the rf space charge wave propagating through the thin epitaxial film. The first dispersion equation solved was that which neglected the effects of diffusion and both surface and volume recombination, while a later equation included these effects. The resulting propagation constant of the rf space charge wave contains information about both its phase velocity and growth. Information regarding impedance of the system and field strength was also obtained. This procedure was repeated at different frequencies and with epitaxial layers of different material properties to investigate their effect upon the performance of this device.

In all cases, it was found that the exact results furnished by the computer agreed very well with the approximate theory for either amplifier with extremely thin semiconductor layers or amplifiers operating at low frequencies, and also the lower frequency experimental work already completed.

C. Device Realization

Because of the encouraging theoretical results on such a device work has been directed toward fabrication of a high frequency space charge wave amplifier, using thin epitaxial GaAs which has been deposited on a semi-insulating GaAs substrate. The coplanar contacts have been fabricated using LPE (liquid phase epitaxy) regrowth techniques which involve etching back the epitaxial GaAs in the exposed contact areas and redepositing heavily doped GaAs in its place, thus forming n^+ contacts, over which metallurgical contacts were made.

An insulator (SiO_2 in this case) was deposited on top of the active region and aluminum was deposited over the insulator to aid in rf coupling and to control the overall amplifier gain. The complete device is shown in Fig. 3.



The first devices have been tested in a microwave microstrip circuit in the frequency range of 7-8 GHz and exhibit internal gains of 3-5 dB above the "cold" straight-through insertion loss of 15 dB. It has been observed that these devices exhibit a much higher dc resistance than theory predicts which may indicate that our contacts are not yet of good quality. Investigation of new contacting procedure and additional device testing and fabrication is now taking place.

II. GUNN OSCILLATOR STUDIES

(C. F. Quate, G. S. Kino and J. A. Higgins)

INTRODUCTION

In this project we are concentrating on the problem of growing relatively pure gallium arsenide epi-layers and semi-insulating substrates. The growth of good quality epi-layers is characterized by the mobility of the electrons at a temperature of $77^{\circ}K$ of the carrier concentration which should be as low as possible. In addition we are planning to fabricate Gunn oscillator devices from these samples and study their characteristics with current flow along the epi-layer. This will be complemented with a theoretical study of the behavior through the use of a computer program which has been developed previously for computing the behavior of Gunn devices.

PRESENT STATUS

This report covers some work done on the materials aspects of GaAs and also computer simulations of Gunn oscillation. Practical long oscillators have also been fabricated to withstand long duty cycles and are reported on herewith.

A. Materials

We have continued work described in previous reports. Quartz crucibles have been used in the place of graphite with much improved results. The obvious implications of this, i.e., that (carbon) graphite does enter the crystal and is electrically active as a donor, are now given the status of probabilities rather than just possibilities. Certainly it seems that a large amount of donor impurities has come from the source materials (arsenic sources). Quality now makes a difference. Those which previously gave a highly compensated product now give p-type material and those which previously gave a less compensated product now give n-type materials.

We have obtained thin layers ($20\ \mu < t < 40\ \mu$) of relatively good carrier concentration (7×10^{14}) and good to fair surface properties. These materials were grown in a vertical system. The same system was used to investigate the behavior of oxygen at different temperatures and some new understanding was obtained of this. We found donor behavior when growing at lower temperatures (< 750), but acceptor behavior when the temperature was above 800. This behavior of oxygen does explain many of the crystal properties we obtained in our earlier efforts (see previous reports).

We are continuing efforts to obtain greater purities. We have fabricated devices from the material grown in the horizontal system as reported in the last report and mounted them on heat sinks which were sufficient to allow us to operate at threshold with continuous dc fields. However, it is still necessary to resort to pulsed operation as we go to higher fields and study the oscillation characteristics. The samples have been mounted in wave-guide circuits and oscillations at 10 GHz have been observed. At the time of routing no quantitative data that can be compared with the computer results has been obtained.

B. Computer Modeling

We have investigated the effect of length of the device on the space charge decay in Gunn oscillators for various values of carrier concentration and one value of frequency. We have found that space charge is more readily extinguished in long devices if the rf E field value is sufficiently high. However, in the event of low rf E field, very high E field values may build up at the anode that could cause breakdown. We have arrived at optimum values of load resistance to device resistance which are very close to the values that result from the uniform field analysis of the LSA mode.